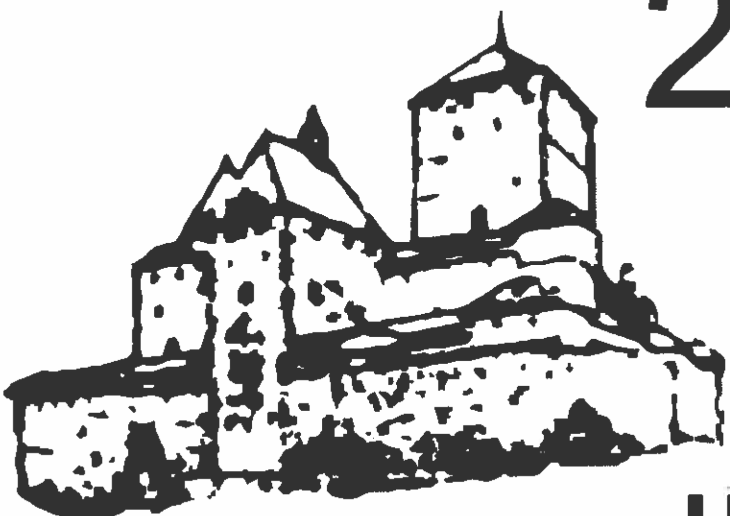
18th INTERNATIONAL WINTERSCHOOL

MAUTERNDORF CASTLE, AUSTRIA

FEB 23-28 2014

NEW DEVELOPMENTS IN SOLID STATE PHYSICS

MAUTERNDORF 2014



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Photonic crystal quantum cascade detector

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An upcoming class of mid-infrared intersubband photodetectors is the quantum cascade detector (QCD) [1]. Compared to quantum well infrared photodetectors (QWIP), QCDs offer a vast design freedom for the electronic band structure. However, to fully exploit that feature, a novel cavity is required.

We present a QCD that is fabricated as photonic crystal slab (PCS) [2]. The PCS is built as purely dielectric structure that utilizes an artificially induced periodic variation of the refractive index (Fig 1). By employing this specifically designed resonant cavity, the QCD is improved in three distinct ways.

The PCS makes the device sensitive to surface normal incident light by coupling external field modes to modes with an electric field component in growth direction [3].

The strongest effect is resonant absorption enhancement. By restricting the propagation freedom of photons to bands, at so-called band-edge states, the photon lifetime is increased significantly. By designing such a state to coincide with the absorption frequency of the QCD, we achieved a signal enhancement of up to a factor of four (Fig 2).

QCDs typically operate around zero bias. Above the background-limited infrared performance temperature T_{BLIP}, noise is dominated by Johnson noise, which is indirectly proportional to the square root of the device resistance [4]. The PCS is fabricated by etching holes in the QCD material. Thus, the resistance of the device is increased. With typical hole radii the device resistance is increased by 50% to 100%.

Further improvement can be achieved by using a QCD with lower material absorption, to match the PCS' quality factor. We envision that by fully exploiting the design freedom of both the QCD and the PCS, mid-infrared photodetector can be pushed towards room temperature operation with reasonable performance.

The authors acknowledge the support by the Austrian Science Fund, project IRON (F2503-N17), the PLATON project 35N within the Austrian NANO initiative and the FP7 EU-project ICARUS.

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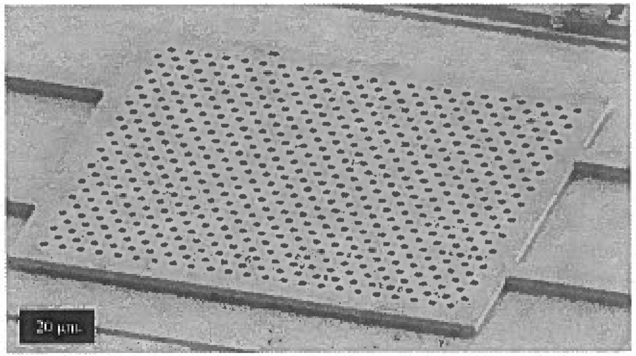

Fig. 1: (a) Scanning electron microscopy image of the fabricated PCS-QCD. The dimensions of the slab are 115 x115 µm, with a thickness of 1.91 µm. It is suspended by four beams.

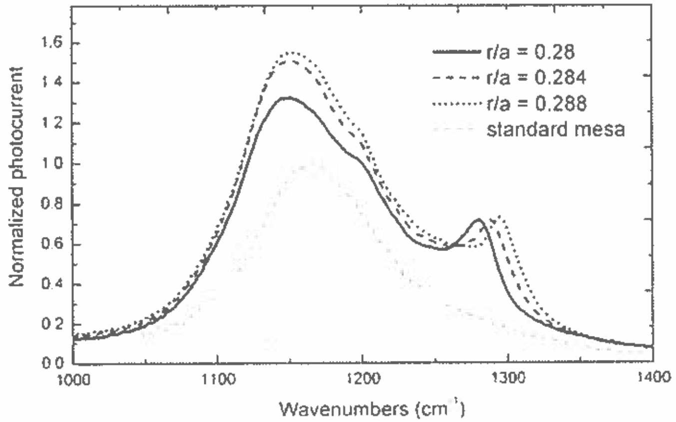

Fig. 2: Photocurrent response of a standard QCD and three PCS-QCD devices at liquid nitrogen temperature. The PCS parameters are $a = 4.5$ µm and slab thickness $d = 1.91$ µm. The figure shows the shift of PCS resonance at 1290 cm^{-1}, in accordance to RPWEM simulations, to higher wavenumbers for larger r/a.

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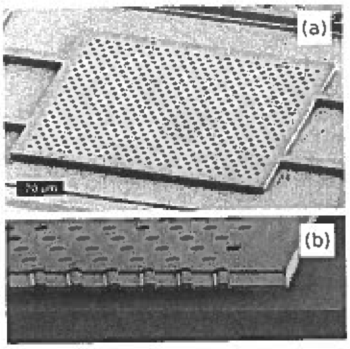
Introduction

Molecules have vibrational resonances that can be excited with mid-infrared radiation. Measuring transmission or reflection spectra of a medium gives information about the molecules present. This creates a high demand for compact sensors with individually adjustable absorption frequencies. An upcoming class of photodetectors for such applications are quantum cascade detectors (QCD). QCDs are very adaptable devices and it's properties can be tailored by a huge amount. To take full advantage a sophisticated cavity is needed. Photonic crystal slabs are a perfect combination for QCDs.

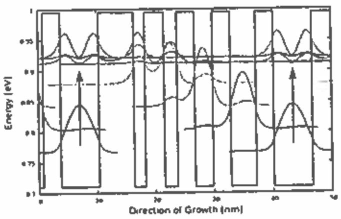
Photonic crystal slab

A Photonic crystal slab (PCS) is a purely dielectric structure that can be used to engineer the behavior of photons. It effectively restricts the propagation freedom of photons to bands inside the Brillouin zone. It is produced by etching a lattice of holes. The so-called photonic bandstructure can be tailored via the PCS parameters: the hole diameter, the lattice constant and the thickness of the slab. Figure (a) shows a scanning electron microscopy image of a PCS and (b) a schematic illustration of the designed structure.



Quantum cascade detector

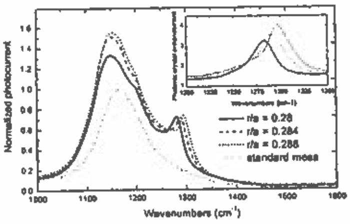
A quantum cascade detector is an upcoming class of photodetectors, based on intersubband transitions in the conduction band. The band-diagram of our QCD is shown in the figure. The active transition occurs between the two energy levels of the broadest well, indicated as blue. The transition energy can be tailored for specific applications by engineering the electronic bandstructure. Only photons with the appropriate energy can excite an electron into the upper level.



There, it can escape into the extractor, eventually reaching the ground level of the next cascade and contributing to the photocurrent.

PCS - QCD

A QCD is a photodetector with vast design freedom. By engineering the band-structure, properties like the absorption coefficient can be varied by more than an order of magnitude.



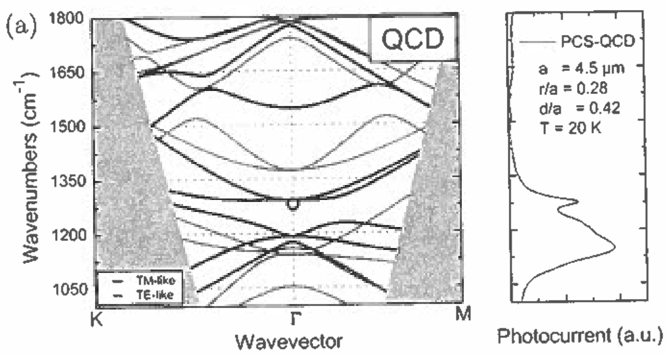
Such a sophisticated device needs a cavity that can keep up. A PCS is perfectly suited. It is fully compatible with the processing technology and is as customizable as a QCD.

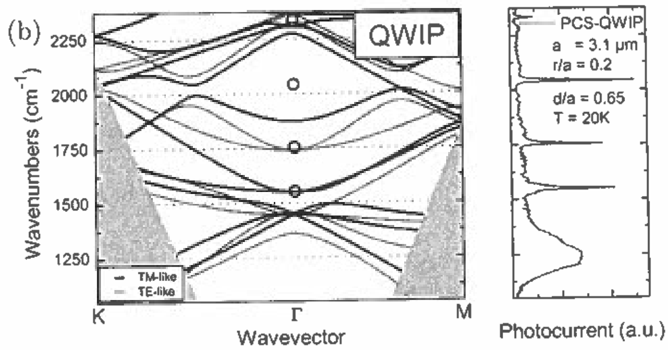
By employing this specifically designed resonant cavity, the performance of the photodetector is improved in three distinct ways.

- At resonance frequencies, a PCS slows down light. Slower light stays longer in the QCD and the absorption probability is increased.
- The PCS couples external field modes to modes with an electric field component in growth direction, which enables us to excite the PCS-QCD with surface normal incident light.
- The construction form of the PCS-QCD inherently increases the resistance. The result is an enhancement of the noise behavior.

PCS - QCD vs. PCS - QWIP

The photocurrent spectra of both a PCS-QCD (a) and a PCS-QWIP (b) are shown. The PCS-QCD shows the broad absorption peak of the QCD and the sharp peak from the PCS resonance. The PCS-QWIP exhibits several PCS resonances at higher energy. This distinction comes from the different operational principles of the two devices. Quantum well infrared photodetectors (QWIPs) are one of the most common mid-infrared detectors. Photon absorption is based on bound-to-quasibound transitions. Photons with very high energy still can, with low probability, contribute to photocurrent. For QCDs, only photons that induce an electronic transition into the upper absorption level contribute to photocurrent.





The PCS, at the resonance frequencies, enhances the photon lifetime. It can compensate for low absorption probabilities (QWIP). Still, photons with enhanced lifetime, but wrong energy, will not contribute to a QCDs photocurrent. Thus, PCS - QCDs are perfectly suited for applications that require sensing of distinct spectral lines, while suppressing detection of side-band radiation.

Outlook

This work showed the functional principle of a PCS-QCD. Future work involves quality factor matching, optimized QCD designs and using a PCS-QCD as foundation for strong coupling experiments.

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